研 究 速 報

3-D Applied Element Method for PP-Band Retrofitted Masonry

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1. Introduction

Masonry along with timber structures are among the oldest structures that are still used nowadays. Despite its advantages as residential structure, masonry is known to perform poorly under seismic loads if unreinforced (Tomaževič, 1999). The 1997 Umbria-Marche, 1999 Bhuj and 2003 Bam earthquakes showed that masonry is rather susceptible and a huge number of masonry collapses are found especially in the region where the poorly designed masonries are concentrated. Moreover, masonry collapse results in huge number of casualties because masonry material tends to break into the small debris leaving insufficient void which reduces the chance of survival.

In order to improve the current situation, retrofitting is indispensable. Recently a retrofitting scheme considering economy and availability of material and labor, namely Polypropylene band (PP-band) mesh retrofitting technique, has been proposed. The method was first proposed by Mayorca (2003). Unlike the former methods, a main objective of this technique is to hold the disintegrated elements together thus preventing the collapse. Mayorca (2003), Meguro *et al.* (2004), and Sathiparan (2005) verified the efficiency of PP-band meshes experimentally under static and dynamic loads. Furthermore, Mayorca (2003) and Guragain (2006) investigated the retrofitted structure behavior numerically.

Several failure mechanisms are observed in masonry structures. Most of them involve three dimensional behavior. With the proposed PP-band retrofitting, the interaction between walls is higher and as a result the seismic resistance is improved. Therefore, three dimensional behavior must be investigated before developing less complicated two dimension analysis and design process. Because PP-band stiffness is rather low compared to masonry, the effect of retrofitted PP-band will play a major role when the structure significantly deforms. Therefore, it is inevitably required a good understanding of three dimensional seismic behavior of masonry structure in the large deformation state. Despite a number of numerical models for structural analysis, few are suitable to simulate masonry in the large deformation range. The Applied Element Method (AEM) is one among these. In this study, we proposed the 3-D AEM, based on previous 2-D AEM for masonry and 3-D AEM for concrete, to simulate three dimensional behaviors for PP-band retrofitted masonry structure.

2. 3-Dimensional Applied Element Method

In AEM, the structure is divided in rigid elements, carrying only the system's mass and damping, connected with normal and shear springs representing the material properties (Figure 1). The stress and strain fields are calculated from the spring deformations. 3-D AEM rigid elements with 6 degrees of freedom each are connected through sets of one normal and two shear springs.

3-D AEM uses an explicit scheme to solve structural problems therefore it is required to assemble the system stiffness matrix. For

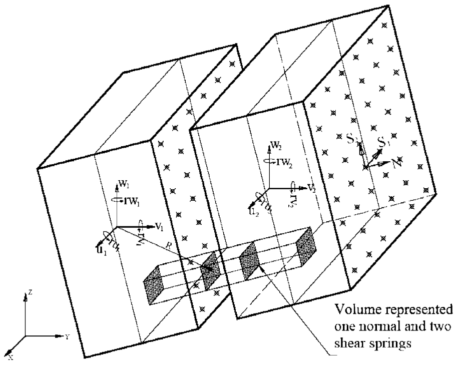

Fig. 1 3-D AEM

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*****Director, Professor, International Center for Urban Safety Engineering, this purpose, it is necessary to sum up the contributions of all the springs around one element to the relevant degrees of freedom. Because each element has six degrees of freedom, the stiffness matrix of each spring is a 12 by 12 matrix whose components were generated by direct stiffness method.

Masonry is constituted by two phases: brick and mortar. Therefore, two types of springs: one inside brick units, brick spring, and the other at the joint interface, brick-mortar spring, are defined Spring formulation may be found in Guragain (2006).

Eigenvalue analysis is also possible with the current version of 3D-AEM. The vector iteration with shifts technique is adopted. This technique is chosen as it provides a practical tool for computing as many pairs of natural vibration frequencies and modes of the structure as desired.

2.1 Masonry Modeling

The material constitutive relation requires spring level stress/strain updating for each loading step in the 3-D AEM. The stiffness changes in accordance to damage that material sustained at local level is required to monitor throughout the loading history. As mentioned earlier, the constitutive law needs to be modified in order to take into account this phenomenon. Such a model should be able to reflect the highly nonlinear behavior of masonry with the fewest number of parameters so that it results in a simple and stable numerical model. Considering these criteria, the damage model of brick masonry proposed by Gambarotta *et al.* (1996) has been chosen to implement in the 3D-AEM for cyclic behavior of the masonry. This constitutive law is able to reflect the important physical phenomena exhibited by masonry under cyclic loading. Details of the model may be found in Guragain (2006).

2.2 PP-Band Mesh Modeling

The PP-band mesh is modeled through beam elements spanning between band intersections points as shown in Figure 2. These ends are then connected to the masonry structure through a set of three springs: normal, shear, and rotational. By appropriately setting the properties of these springs, it is possible to consider all possible connecting conditions between mesh and structure. For instance, if there is a wire connector at that particular location, all three springs have values proportional to the connector properties. On the other hand, if there is no connector and no mortar overlay, the normal spring only works in compression, i.e. when the mesh and the structure are in contact. As for the shear and rotation springs, there values are almost zero. This would not be case if there was mortar overlay.

The direct implication of a model as the one described above is the considerable increase of degrees of freedom of the system because each intersection point is associated with six more degrees of freedom. A 3-dimensional analysis by itself also involves the solution of systems with large number of degrees of freedom. Therefore, it was absolutely necessary to optimize the algorithms used to solve the equations of motion. This step was successfully implemented.

The material model used for each PP-band beam element was elastic in tension as shown in Figure 3. No compression forces were taken by the beam element. The beam elements were defined so as to have almost no moment resistance at their ends.

3. Model Verification

The 3D-AEM model was verified using the experimental data obtained by Sathiparan (2005). The non-retrofitted and retrofitted wallettes, shown in Figure 4 and Figure 5, were 475 × 235 × 50 mm^3 and consisted of 6 rows of 6 bricks each. The PP-band mesh was made of 6 mm-width, 0.32 mm-thick PP-bands placed at 40 mm pitch. A total of 6 wire connectors were used to attach the meshes to the wallettes. The wallettes were simply supported by high strength steel rods in both ends. The masonry wallettes were tested under line load using another steel rod of 200 mm diameter in the mid span.

The material properties used for the masonry are summarized in Table 1. The PP-band mesh stiffness was set equal to 9.375 MPa based on data available from tension tests.

The models used for non-retrofitted and retrofitted models are shown in Figure 6.

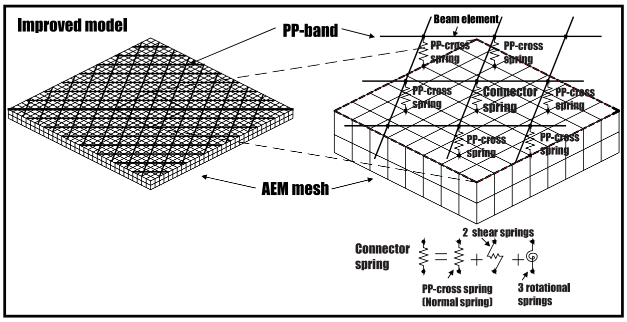


Fig. 2 3D-AEM mesh modeling

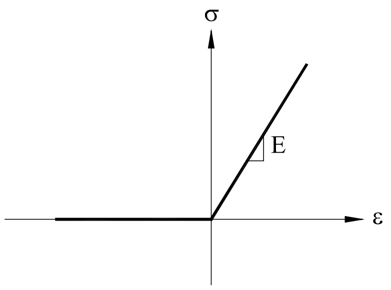


Fig. 3 Material model for PP-band beam element

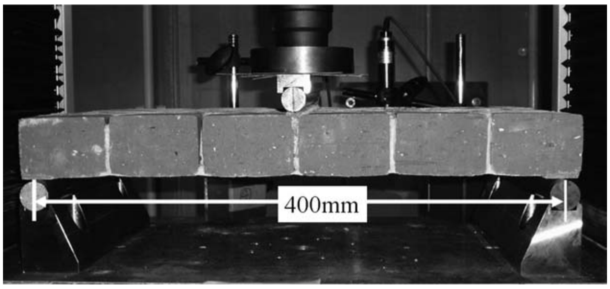


Fig. 4 Retrofitted masonry wallet tested for out of plane

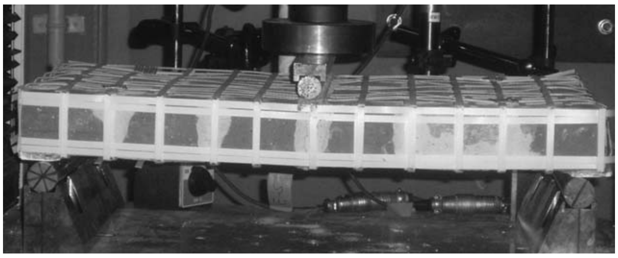
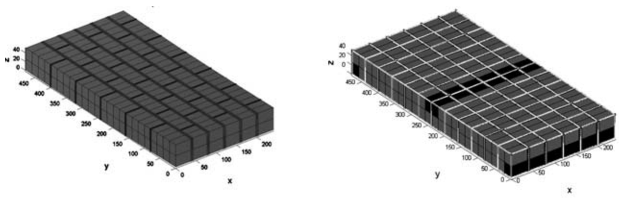


Fig. 5 Boundary condition and loading of the masonry wallet for out of plane test

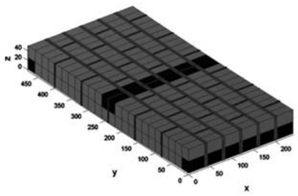
Table 1 Material properties used for the modeling of out-of-plane masonry wallettes

	Young's modulus E (kN/mm²)	Shear modulus G (kN/mm²)	Tensile strength σ_{ct} (kN/mm²)	Shear strength τ_{ct} (kN/mm²)	Friction coeff. μ	β	$1/C_{mt}$ (kN/mm³)
Mortar	0.5	0.25	$0.16e^{-3}$	$0.22e^{-3}$	0.6	0.9	1/30
Brick	15.0	7.5	NA	NA	NA	NA	NA

NA: Not applicable



(a) Non-retrofitted wallette (b) Retrofitted wallette



(b) Boundary and loading condition (top dark elements: loading point, bottom dark elements: support)

Fig. 6 Boundary condition and loading of the masonry wallette for out of plane test

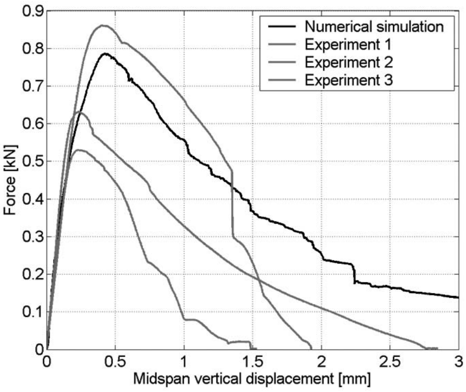


Fig. 7 Numerical and experimental force-deformation curves for non-retrofitted wallettes. (Experiments by Sathiparan, 2005)

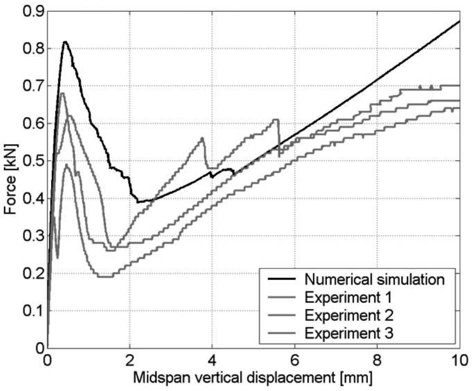
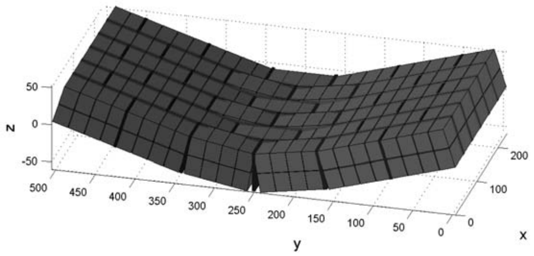


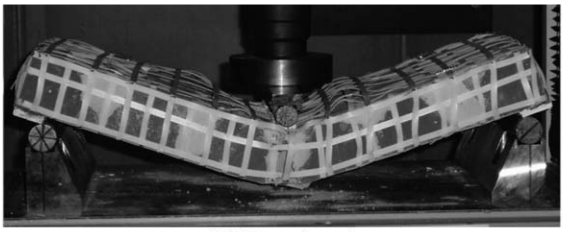
Fig. 8 Numerical and experimental force-deformation curves for retrofitted wallettes. (Experiments by Sathiparan, 2005)

(a) Experiment

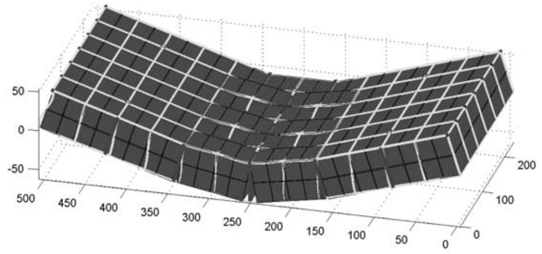


(b) Numerical simulation (scale factor: 20; midspan vertical displacement=3mm)

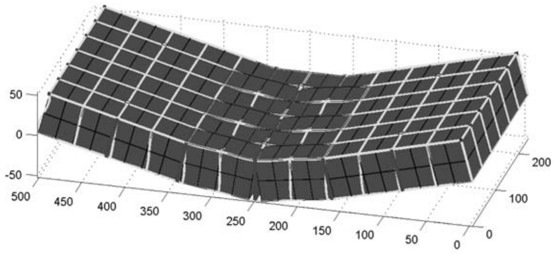
Fig. 9 Comparison of numerical simulation and experimental deformed shapes for non-retrofitted masonry



(a) Experiment



(b) Numerical simulation (scale factor: 20; midspan vertical displacement=3mm)



(c) Numerical simulation (scale factor: 5; midspan vertical displacement=10mm)

Fig. 10 Comparison of numerical simulation and experimental deformed shapes for non-retrofitted masonry

Figures 7 and 8 show the comparison of numerical and experimental simulations for non-retrofitted and retrofitted wallettes, respectively. It can be seen that in both cases, the model could accurately capture the force-deformation relationships.

The agreement between experiments and numerical simulation could also be observed in the crack patterns and deformed shapes (Figure 9 and 10).

4. Conclusion

The 3-D AEM for simulating static behavior of PP-band retrofitted masonry was developed. The main improvements in this version are the rectangular prism AEM element which helps reducing the element number and the additional beam element and connected spring allowing AEM for simulating PP-band. The verification for 3-D AEM for PP-band retrofitted masonry for the out of plane test was carried out. The verification result shows that with the suitable selected parameter, the behavior of masonry can be closely reproduced.

(Manuscript received, January 22, 2008)

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